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A COMPARISON OF WAVE CONTOUR AND CONFIDENCE DOMAIN APPROACHES TO DEFINING THE WAVE ENVIRONMENT FOR SEAKEEPING INVESTIGATIONS

by

N.K. Bales

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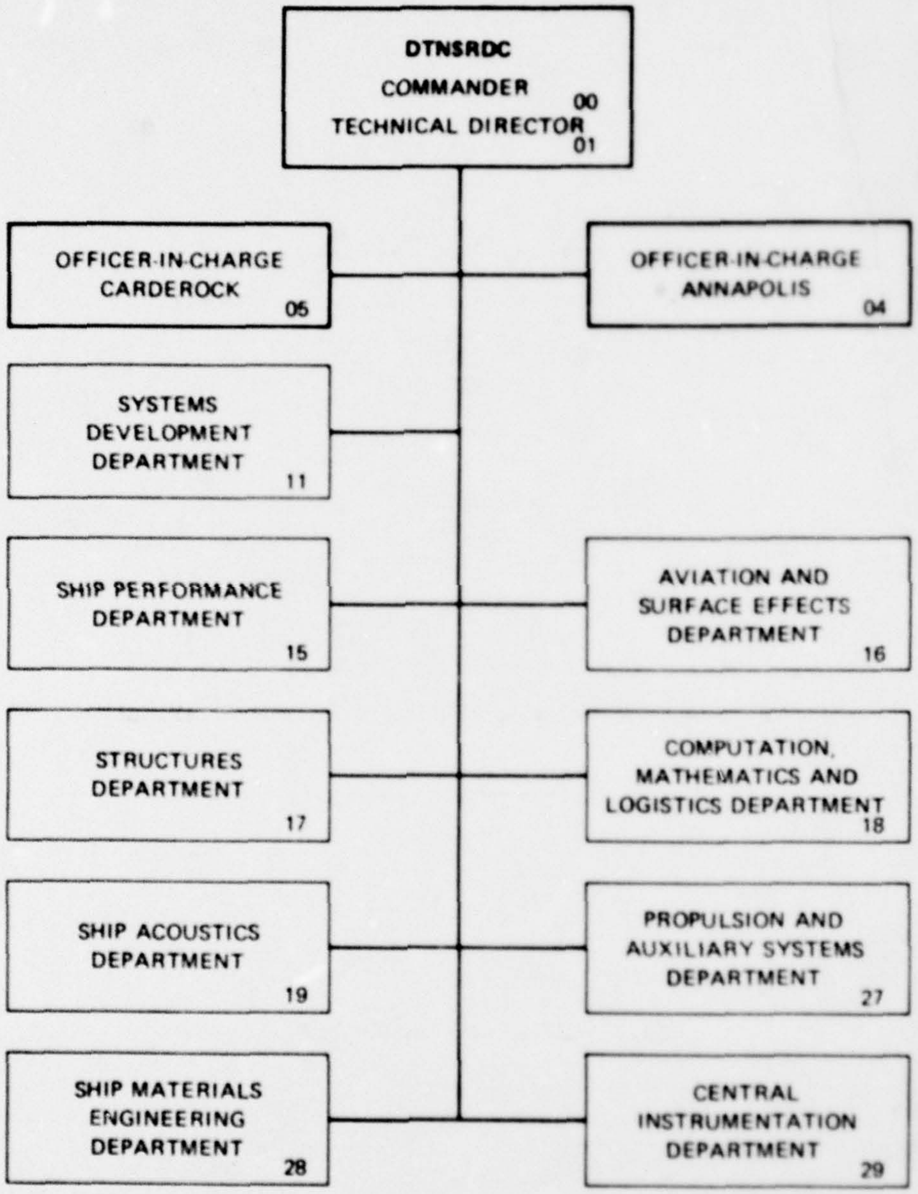

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Wave contour and confidence domain approaches to bounding the wave environment, though similar in concept, are shown to produce widely differing results for similar conditions. A comparative analysis is performed to identify the causes for these differences. It is found that the calibration equations used to convert visually observed wave characteristics to wave statistics in the confidence domain approach are of questionable validity, and that the methodology used to define wave contours is deficient. A revised approach to bounding the wave environment is delineated and implemented for two cases.

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ABSTRACT

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ADMINISTRATIVE INFORMATION

The work described herein was funded by the Conventional Ship Seakeeping Research and Development Program under Project Number 62543 and Block Number SF 43 421 202. The work was performed at the David W. Taylor Naval Ship Research and Development Center. There it was identified by Segment 20 of Work Unit Number 1-1504-100.

INTRODUCTION

During the spring of 1975, the present author was involved in a project intended to establish freeboard requirements for a surface combatant then being designed. Preliminary results indicated that the freeboards required to insure an acceptably-dry foredeck continued to increase slowly with increases in modal wave period. Hence, it was necessary to bound the wave environment considered in order to obtain an unequivocal solution to the required freeboard problem.

The approach to this problem which evolved was to derive a "wave contour" which encompassed some specified, high percentage of the wave height and wave period combinations expected to occur in the ocean area and season of primary concern for the ship under consideration. By neglecting wave conditions outside the contour, a unique solution to the required freeboard problem could be obtained. In addition, wave contours proved to be of value in comparing the severities of different operational areas and in general assessments of seakeeping performance.

The contour approach to bounding the wave environment was refined in the course of subsequent work, and was made generally available as part of a paper on establishing minimum freeboard requirements which the present author gave during the spring of 1979: Reference 1.* In Reference 1, wave contours were presented in the form of closed curves in coordinates of significant wave height versus modal wave period. Each such contour was said to bound a specified percentage of the wave height and wave period combinations expected to occur in a given ocean area and during a given season.

In Reference 2, Ochi described a "confidence domain" approach to characterizing the wave environment. His confidence domains, like the wave contours used by the present author in Reference 1, took the form of closed curves in wave height-wave period coordinates. The confidence domains were, again like the wave contours, said to bound a specified percentage of the wave height and wave period combinations expected to occur in a given area and during a given season.

In view of their conceptual similarities, one might reasonalbly anticipate that a wave contour and a confidence domain applicable to similar ocean areas, seasons, and probability levels would be very much alike. Figure 1 shows that such is not the case. This figure compares a wave contour used in Reference 1 with a confidence domain from Reference 2. The area and season conditions for the two curves are not identical, but those differences appear inadequate to explain the differences in the final results.

It is thought that differences in wave environment bounds on the order of those exhibited by Figure 1 could lead to different design decisions. For instance, it appears that a large ship or a vessel designed to have long natural periods of motion (such as a SWATH) would be found to experience considerably more performance degradation within the boundaries of the Figure 1 confidence domain than within those of the nominally

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*A Complete listing of references is given on page 13.

comparable wave contour shown in the same figure. In view of the potential impact of the differences between the wave contour and confidence domain approaches to bounding the wave environment on design decisions, it was decided to explore the reasons for these differences. The results of this exploration are reported hereinafter.

COMPARATIVE ANALYSIS

The wave contour in Figure 1 was derived from visually-observed wave data presented by Hogben and Lumb in Reference 3. These data were compiled from weather reports submitted by ships of opportunity. Hogben and Lumb provide a global data base, but it is biased to British merchant ship routes. The North Atlantic is extensively covered.

The methodology used to construct wave contours is described in detail by the present author in Reference 4. In principle, a plane defined by an assigned value of the joint probability density function of wave height and wave period is passed through the unit volume bounded by that function. The plane divides the volume into two parts: say P above the plane; and hence, 1-P below the plane. Then the contour along which the plane intersects the surface of the joint probability density function is said to bound 100 P percent of the wave height and wave period combinations. Observed wave heights and periods are converted to significant wave heights and modal wave periods using the calibration equations derived by Nordenström in Reference 5.

Nordenström calibration equations are regression functions derived from a correlation analysis of observed and measured wave data. The observed and measured values of each wave characteristic (height and period) are assumed to be governed by the bivariate, log-normal distribution. The particular data set used consists of weather ship observations and ship-borne wavemeter measurements applicable to Ocean Weather Stations A, I, J, and K. (See Figure 2 for the locations of these Stations.) The measured data is treated in the form of power spectral density estimates of average zero crossing period and significant wave height. These estimates are taken from the results given by Moskowitz, et al., in Reference 6.

An empirical relationship between average zero crossing period and modal wave period is derived by Nordenström the course of his Reference 5 work on calibrations. The present author, however, used the theoretical relationship between the two parameters for his application of Nordenström's results. The theoretical relationship assumes a narrow spectrum, and leads to values of modal wave period eight percent lower than the Nordenström relationship.

The confidence domain in Figure 1 was derived from visually observed wave data presented by Walden in Reference 7. The Walden data is compiled from observations made aboard weather ships in the North Atlantic. Walden's data applies to Ocean Weather Stations A, B, C, D, E, I, J, K, and M. (Figure 2 shows the locations of these Stations.) Ochi did not consider Stations E and M in deriving the mean North Atlantic confidence domain which is reproduced in Figure 1. However, he did derive a 95 percent confidence domain for each of the Stations considered by Walden.

Ochi employed sophisticated statistical and mathematical methods to derive his confidence domains. The joint distribution of wave height and wave period is taken to be log-normal, and is transformed into polar coordinates with their origin at the most probable combination of wave height and wave period. Integrations are performed radially outward from this origin to define a set of wave height and wave period combinations for which the integrals equal a specified probability, say P. A curve faired through the set of points so-defined is the confidence domain which bounds 100 P percent of the wave height and wave period combinations.

Ochi converts from visually-observed wave height and wave period to significant wave height and average zero crossing period using calibration equations which he derives in Reference 2. He first shows that the measured and observed parameters are individually log-normal. Then the measured and observed distributions for each pair of parameters are equated to obtain calibration equations which make the two distributions identical.

The data which Ochi uses for calibration are applicable to Stations I and J as shown in Figure 2. The observations are those reported by Walden. The measurements for Station I are given by Draper and Squire in Reference 8 while those for Station J are from Draper and Whitaker in Reference 9. The Draper, et al., data were measured using ship-borne wavementers and reduced by counting zero crossing periods and measuring wave heights to obtain a significant value thereof. Ochi converted from average zero crossing period to modal period using the theoretical relationship between the two parameters.

From the foregoing descriptions, it is evident that there are three possible reasons for the differences between the wave contour and the nominally-similar confidence domain shown in Figure 1. These are:

1. Differences in the wave data bases employed,
2. Differences in the methodologies employed to construct the bounding curves, and
3. Differences in the calibration equations used to convert from visually-observed wave characteristics to statistically-defined wave characteristics.

Each of these possibilities is explored in the following paragraphs.

The effect of the differences in calibration equations is easily isolated. Ochi's Reference 2 calibrations lead to generally higher modal wave periods than do those given by Nordenström in Reference 5. Significant wave heights show a mixed trend. Those based on the Ochi calibration are slightly lower for small observed heights, but considerably higher for large observed heights.

Figure 3 illustrates these differences. It reproduces the results presented in Figure 1 and adds to them a version of the confidence domain curve which has been transformed to reflect the Nordenström calibrations as given in Reference 5. The effect of the differences in the calibration curves is seen to be important. However, major differences remain between the wave contour and the confidence domain as transformed.

In Reference 2, Ochi tabulates measured wave data from Draper and Squire (Reference 8), and computes confidence domains for this data. By computing a wave contour from the cited tabulation and comparing it to a given confidence domain applicable to the same probability level, the effect of differences in methodology can be isolated. The results of such an exercise are presented in Figure 4. The effect of methodology is seen to be less dramatic than that of calibration as depicted by Figure 3. The wave contour and confidence domain appear that they could be, as they are, different interpretations of the same data base.

The effect of data base differences cannot be isolated in as definitive a manner as those of calibration and methodology. The Walden data in Reference 6, which Ochi used to define confidence domains, is for specific ocean weather ship locations. The Hogben and Lumb data in Reference 3, which the present author used to define wave contours, applies to various ocean areas which typically measure 10 degrees of latitude by 30 of longitude. Hence, no exact identities exist between the two data bases of primary interest. It can be pointed out that the Hogben and Lumb data is subject to a fair weather bias not present in the Walden data. So, if "spatially equivalent" data from the two sources existed, one might reasonably expect that a bounding curve derived from the Hogben and Lumb data would encompass fewer steep and/or high waves than one from the Walden data.

Some quantitative information can be gleaned by considering a secondary data base. The measured wave data from Draper and Squire which was introduced earlier in the context of methodology differences is applicable to Station I. In addition to deriving confidence domains from this data, Ochi derives a confidence domain from the Walden data for Station I. Comparing these two results shows that the differences involved are rarely more than one meter in height and/or one second in period.

Even if the differences between the Hogben and Lumb and Walden data bases lead to bounding curve differences two or three times as large as those just discussed, they will be far smaller than the differences due to calibration. Thus, the present author holds the opinion that calibration equation differences account for the majority of the discrepancy found to exist between nominally equivalent wave contours and confidence domains. The methodologies used to derive these bounding curves have a significant but lesser impact on the differences between them. The effect of data base differences is ill-defined, but probably more on the order of those associated with methodology than of those associated with calibration.

CRITIQUE

The present author has one major reservation as to the validity of Ochi's confidence domain work. On the other hand, the methodology employed by Ochi to construct confidence domains is thought to have an important advantage over that which the present author has used to construct wave contours. Each of these matters is described in detail in the following paragraphs.

It was concluded in the preceding section that differences in the calibration equations used appeared to be the major cause of the discrepancies between nominally equivalent wave contours and confidence domains. It is, then, the differences in wave period calibration which play the dominant role in creating the potential impact of the differences between wave contour and confidence domain characterizations on design decisions. Ochi's wave period calibration is the present author's "one major reservation" regarding the validity of his work on confidence domain.

On the surface of it, Ochi's logic in equating the distributions of visually observed and measured wave parameters to derive calibrations appears unassailable. However, there exists some uncertainty as to whether or not the measurements used are really sea truth. Nordenström rejected the Draper and Squire/Draper and Whitaker data employed by Ochi

as unsuitable for use in his calibration effort because he felt that these data did not properly reflect the presence of low-period waves. His argument was based upon the fact that ship-borne wavementers attenuate high frequency/low period waves; and that the effect of this attenuation can be properly accounted for only if the data are spectral analyzed using a frequency-dependent calibration curve.

A detailed reading of Reference 8 (Draper and Squire) tends to support Nordenström's arguments. In their text, Draper and Squire state that the ship-borne wavementer does not record waves with periods of less than about 5 seconds. One of their discussers, Scott, is critical of this matter. In rebuttal to Scott, Draper and Squire say that 5 seconds is, in fact, the period at which the output of the ship-borne wavementer is attenuated by half; and that they chose not to use such data. Their results, in fact, show no average zero crossing periods less than 6 seconds, i.e., no modal periods less than 8.5 seconds under the theoretical relationship.

The present author would like to add one point to the argument advanced by Nordenström. This will be a physical rather than a statistical argument. It is, in this context, of interest to note how two decades of exposure have increased the profession's tolerance toward statistical proofs. When Jasper placed the log-normal hypothesis before the profession in 1956 (see Reference 10), several of his discussers, among them Korvin-Kroukovsky, Szebeheley, Pierson, Press, and Gumbel, were critical of the fact that he could provide no physical rationale for his successful use of the log-normal distribution. When Ochi presented his Referene 2 paper, only St. Denis came forward to note that his success with the log-normal distribution was "perhaps fortuitous."

Ocean Weather Stations B, C, D, I, J and K lie within the latitude range of the prevailing westerlies. Stations A and E are near the limits of this range. Station M, lying east of Iceland, does not appear to be subject to the prevailing westerlies. In this context, it is of interest to note that Ochi excluded Stations E and M from his definition of the

"mean North Atlantic" on the grounds that confidence domains constructed for them included fewer high waves than did those for the other Stations which Walden considered.

In the latitude range of the prevailing westerlies, it is reasonable to hypothesize that most seas in the easterly longitudes will be growing. As one moves west, it seems that the proportion of fully-developed and/or decaying seas should increase. This hypothesis can be tested using the Walden data.

The Pierson-Moskowitz relationship for fully-developed seas, Reference 11, can be transformed to visually-observed wave height and period coordinates using the calibration equations advanced by Ochi and by Nordenström. Figure 5 illustrates the results of such an exercise. This figure also shows a step-wise approximation to the growing sea area defined by each of the curves. The steps used are based on the wave height-wave period cells employed by Walden for his tabulations. By summing the Walden data for all cells within the growth area defined for each curve, we can approximate the percentage of growing seas implied by each set of calibration equations considered.

The percentages of growing seas were approximated as described above for each Station considered by Walden. Figure 6 presents a plot of these results as a function of longitude. Points are shown for all Stations, but the lines connect only those points thought to be firmly within the latitude range of the prevailing westerlies. The results based on Nordenström's calibration equations support the hypothesis cited above rather well. On the other hand, the Ochi calibrations indicate that growing seas are extremely rare throughout the North Atlantic.

Turning now to the question of methodology, the present author feels that the polar integration approach used by Ochi to derive confidence domains is superior to the simple procedure of dividing the joint probability density function of wave height and period which was employed for

deriving wave contours. By integrating radially outward from the centroid of the wave height-wave period distribution, the confidence domain methodology accounts for conditions which are excluded by a nominally equivalent wave contour. The conditions in question are those which lie beneath the plane used to divide the density function yet are within the boundaries of the resulting contour. The end effect is that the confidence domain bounds a given percentage of the wave environment within a smaller area than does a wave contour applicable to the same conditions. Minimization of the bounding area is, of course, intuitively appealing; and no justification exists for excepting this particular class of conditions in defining a wave contour.

It is to be hoped that the pending publication of a hindcast wave climatology, as outlined by S. Bales and Cummins in Reference 12, will put the issue of "calibrations" to rest once and for all. The same data base should admit rigourous testing of the log-normal and other hypotheses as to the long-term, statistical behavior of ocean waves. In the interim, though, we require some method to bound the wave environment.

The present author is inclined to continue employing visually observed wave data from Hogben and Lumb, and to continue using Nordenström's calibration equations. As to methodology, the present author would like to use a procedure comparable to Ochi's but without the log-normal hypothesis. This approach embodies a contradiction in that the Nordemström calibrations are based on the log-normal hypothesis. Two circumstances mitigate this contradiction. Firstly, the log-normal hypothesis has not been tested for the Hogben and Lumb data; and the known weaknesses of these data would leave the results of such tests open to criticism on the grounds of poor realism. Secondly, the results obtained above in the context of the effects of the prevailing westerlies lend credence to the Nordenström calibrations independent of the assumptions which underlie their derivations.

An implementation of the approach just discussed is described in the following section of this report.

REVISED METHODOLOGY

As indicated in the preceding section, the intent of the present effort is to develop an approach to bounding the wave environment which employs the Hogben and Lumb data base, the Nordenström calibrations, and a methodology which is similar to that used by Ochi to define confidence domains but differs from Ochi's methodology in that it does not require the log-normal hypothesis. The initial attempt made was to perform purely numerical, polar integrations over the Hogben and Lumb data. This failed. So did similar attempts based on the Walden and on the Draper and Squire data. The difficulty arose from the fact that the height-period grids associated with these data bases are, especially for low values of the parameters, too coarse to support the rather complex numerical procedures required. As Ochi performed these integrations, the entire grid of observed frequencies was first reduced to the five parameters characterizing the bivariate, log-normal distribution. Then the details of the coordinate transformation and integration were accommodated by the known form of the distribution function.

It is possible that an extensive, computer-aided effort including some data fairing could have resolved the difficulties associated with direct polar integration of observed wave data. However, such an effort could not be undertaken within the scope of this work. Fortunately, a viable alternative was suggested by Mr. E. N. Comstock of the Naval Sea Systems Command. It was to supplement the present wave contour definition by postulating a vertical cylinder having the cross section of the existing contour. Then the contour would be said to encompass the percentage of wave conditions within the cylinder rather than just those above the plane defining the contour as in the original definition.

This alternative not only accounts for the objections to the original wave contour methodology which were cited in the preceding section, but affords a considerable simplification in contour definition. As detailed by the present author in Reference 4, wave contour definition requires an initial data transformation to allow working with the joint probability

density function. The subsequent integration requires the inverse of the original transformation. Under the cylinder approach, these transformations can be omitted. The intersecting plane can be defined directly in terms of the joint probability of occurrence of wave height and wave period, and the probability of occurrence of wave height and wave period combinations within the cylinder thus defined can be obtained by a direct summation.

This simplification has an intuitively appealing spin-off effect. The boundary of the contour as well as the region which it encompasses now has physical significance. Under the original wave contour definition, the boundary of the wave contour represented a constant value of the joint probability density function of wave height and wave period; and this quantity has no physical significance. Using the cylinder definition, though, the boundary of the wave contour represents the joint probability of occurrence of the wave height and wave period combinations lying along it. This quantity gives us an indication of the rarity of the extreme wave conditions associated with a given contour.

Figure 7 compares wave contours derived from the original and from the cylinder definition. The joint probability level used to define the cylinder version of the contour is supplied. It can be seen that the cylinder definition results in a significant reduction in the area enclosed by the contour.

A family of wave contours for winter, northern North Atlantic operation is presented in Figure 8. A similar family for world-wide, all-season operation is presented in Figure 9. These contours were derived from the Hogben and Lumb data using the Nordenström calibrations and the cylinder definition described above. The world-wide, all-season contours in Figure 9 use all of the data presented by Hogben and Lumb. The Figure 8 contours for the northern North Atlantic in winter use the Hogben and Lumb data for Areas 1 through 4 and 6 through 11 for the months of December, January, and February. The present author will employ the families of wave contours given in Figures 8 and 9 for ongoing efforts requiring the use of wave environment bounds. Revisions will be considered when hindcast climatology data (Reference 12) becomes available.

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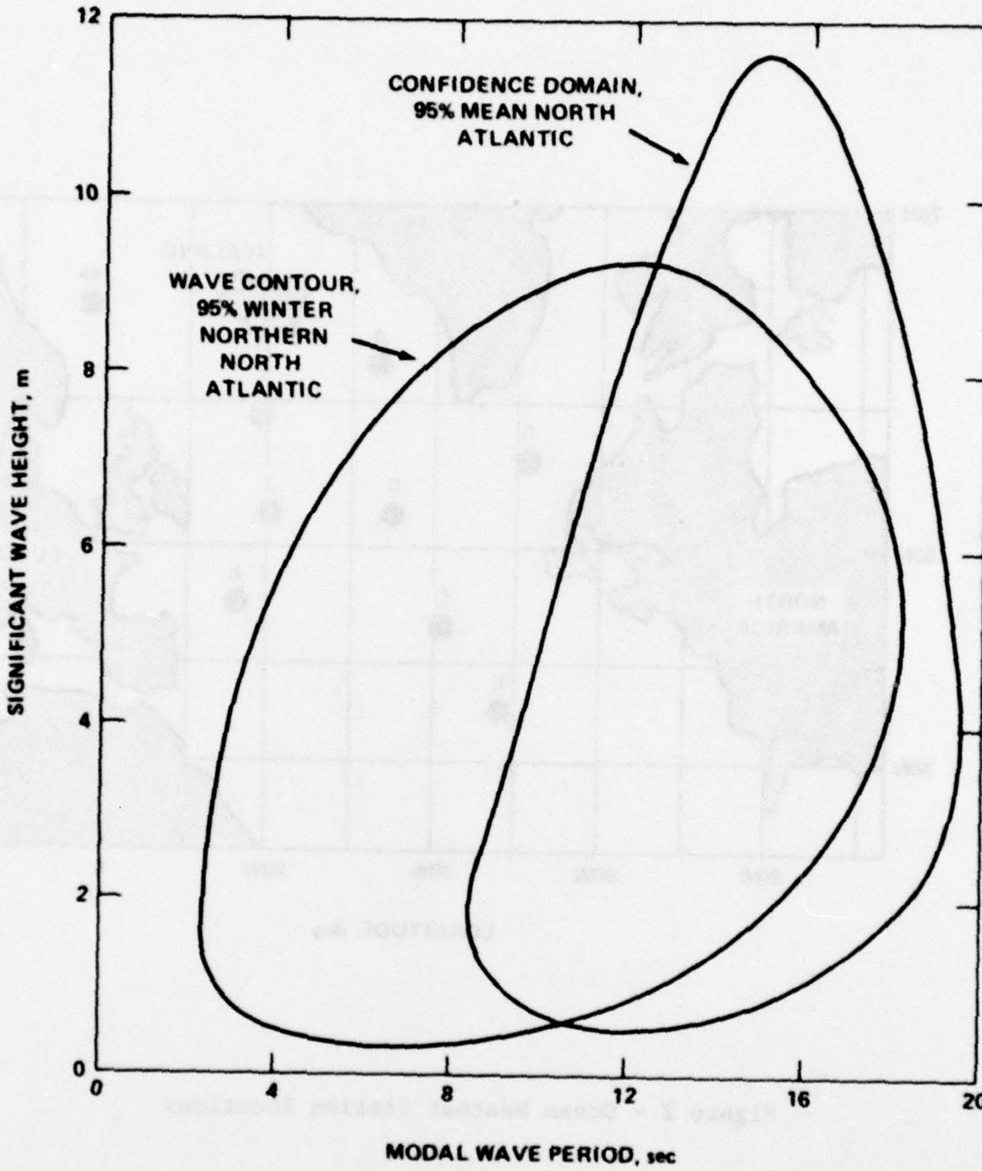

Figure 1 - Comparison of a Wave Contour and a Nominally-Equivalent Confidence Domain

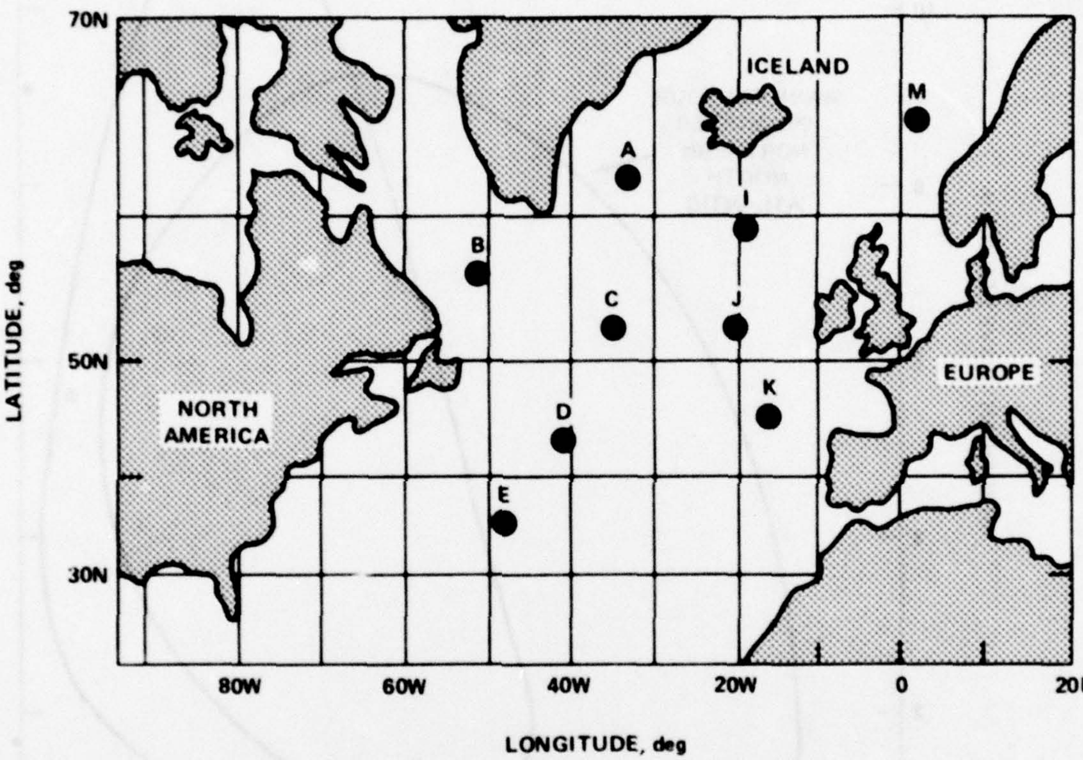

Figure 2 - Ocean Weather Station Locations

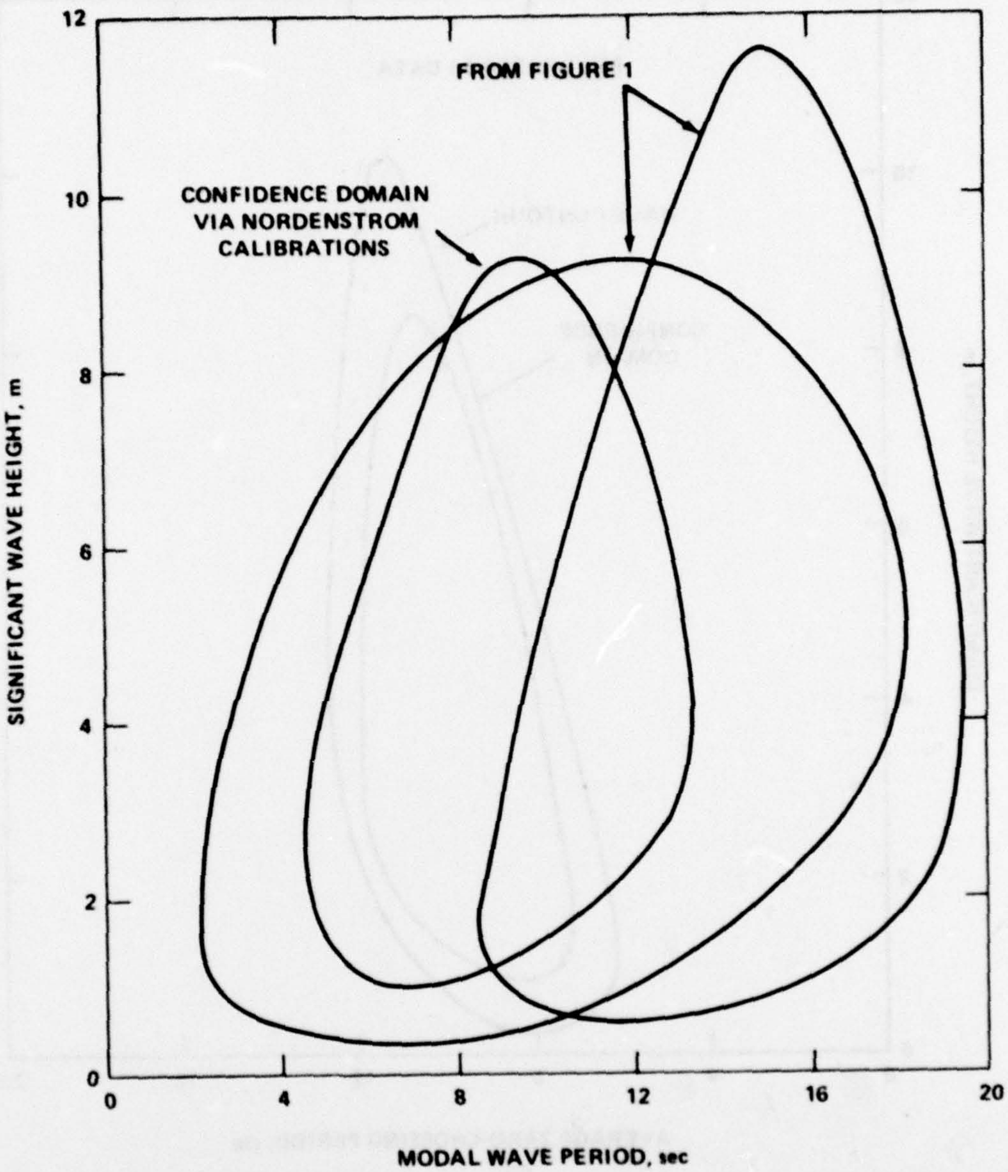

Figure 3 - Influence of Calibration Equations

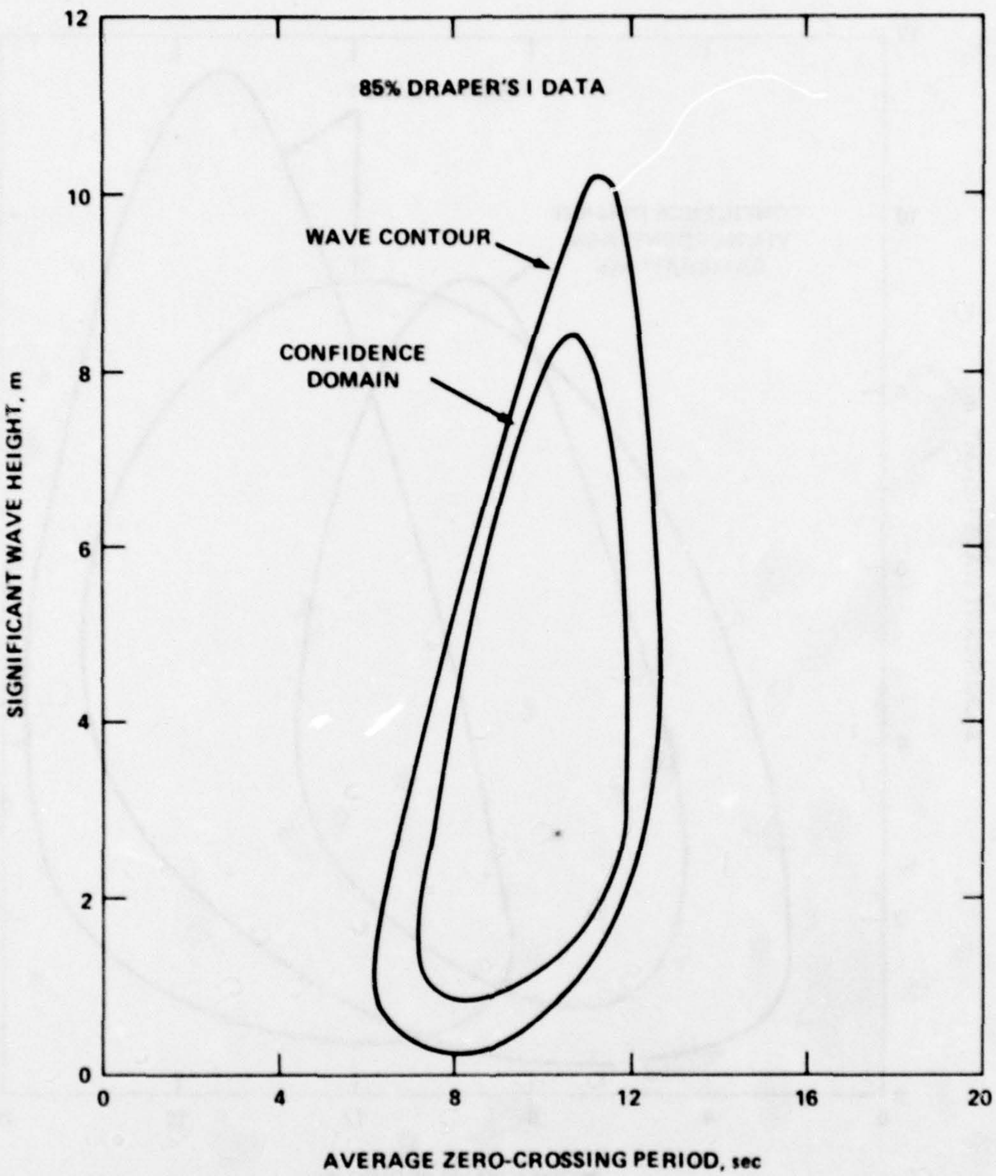

Figure 4 - Influence of Methodology

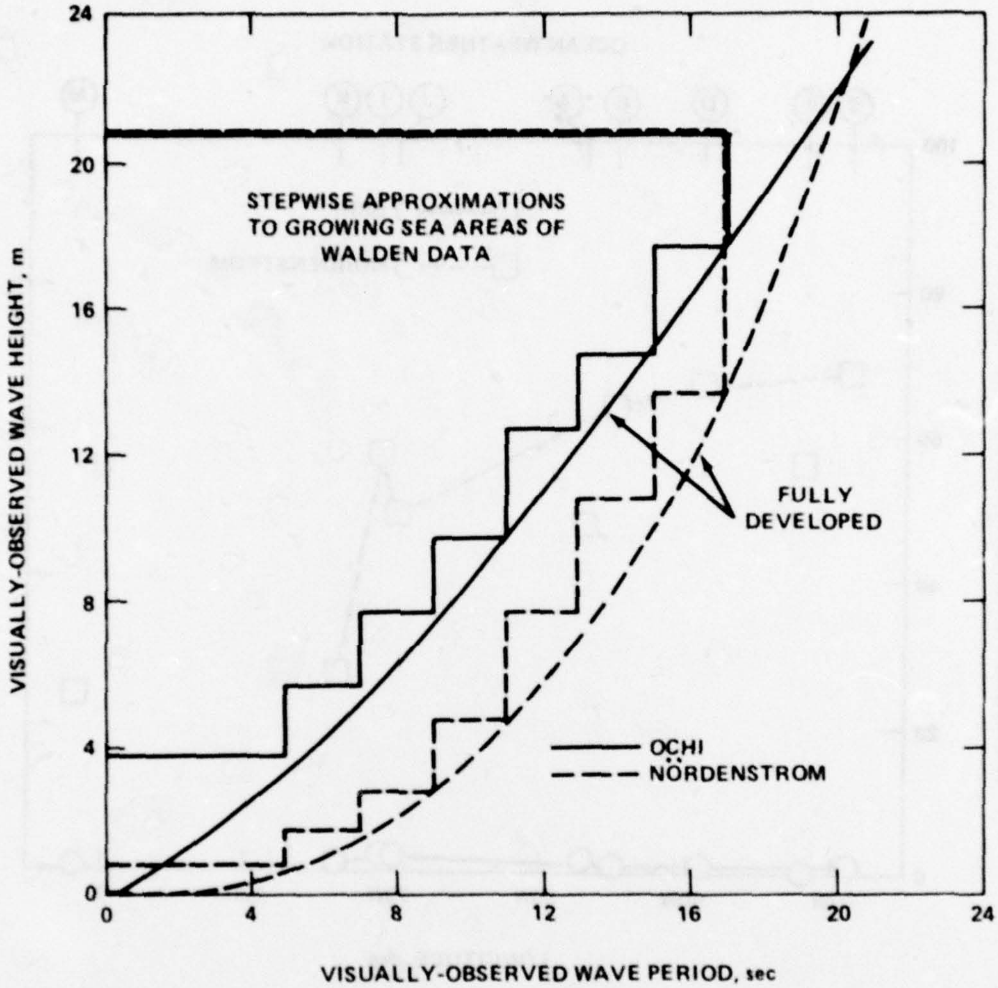

Figure 5 - Fully-Developed Sea Relationships in Visual Coordinates

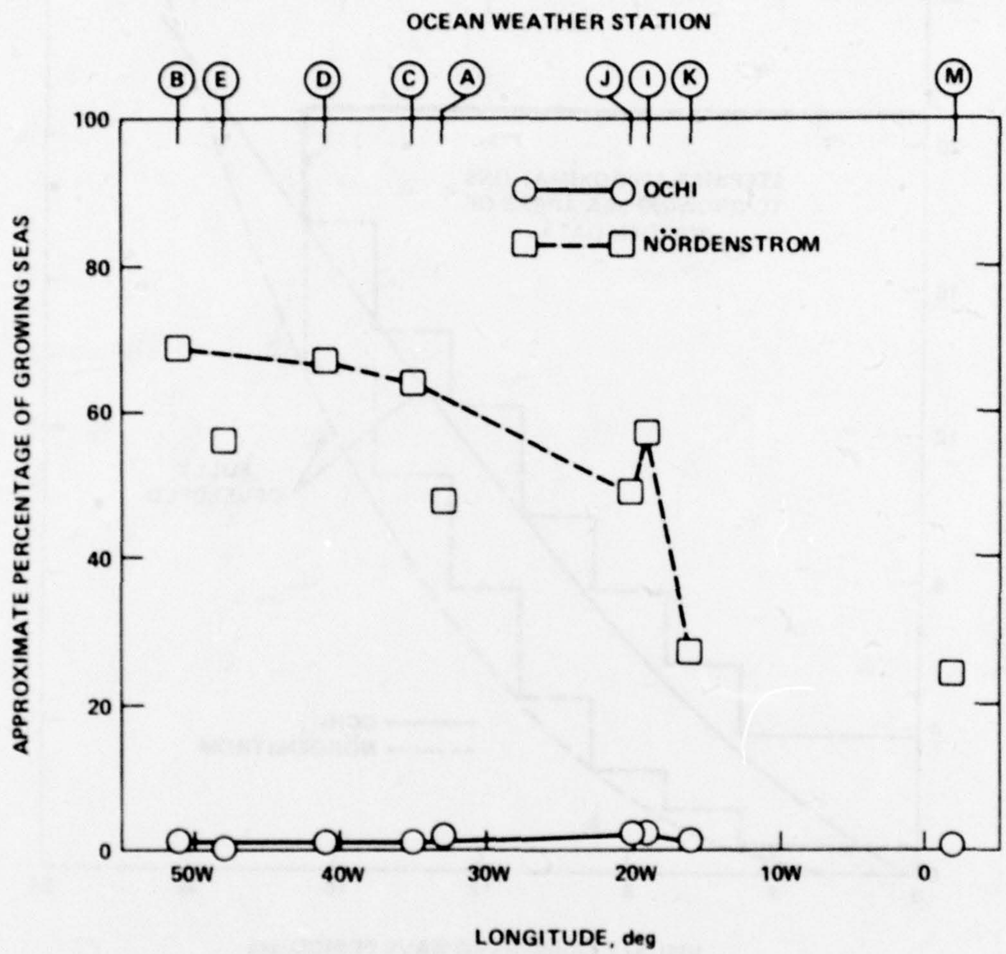

Figure 6 - Approximate Percentage of Growing Seas as a Function of Longitude

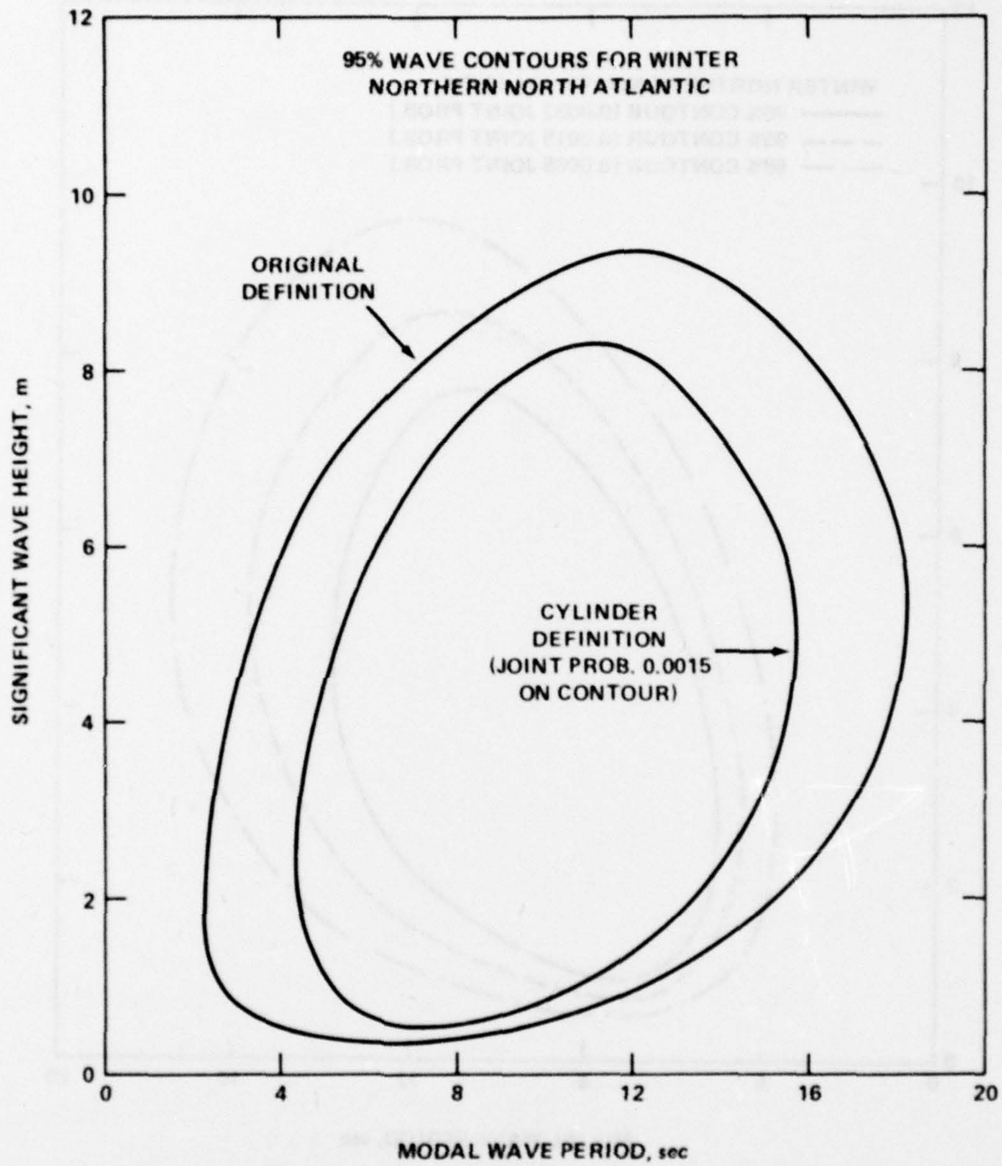

Figure 7 - Comparison of Original and Cylinder-Definition Contours

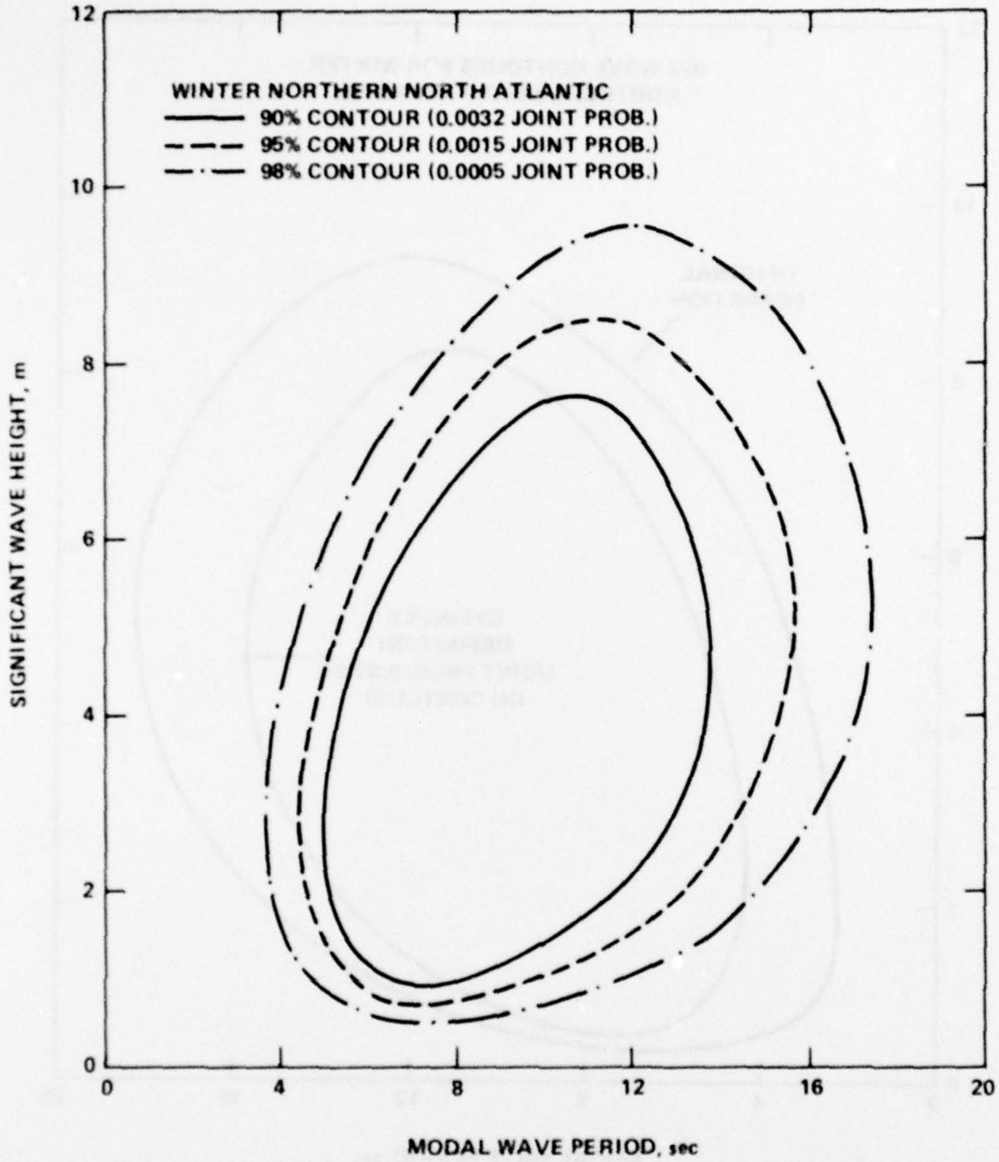

Figure 8 - A Family of Cylinder-Definition Wave Contours for the Northern North Atlantic During the Winter Months

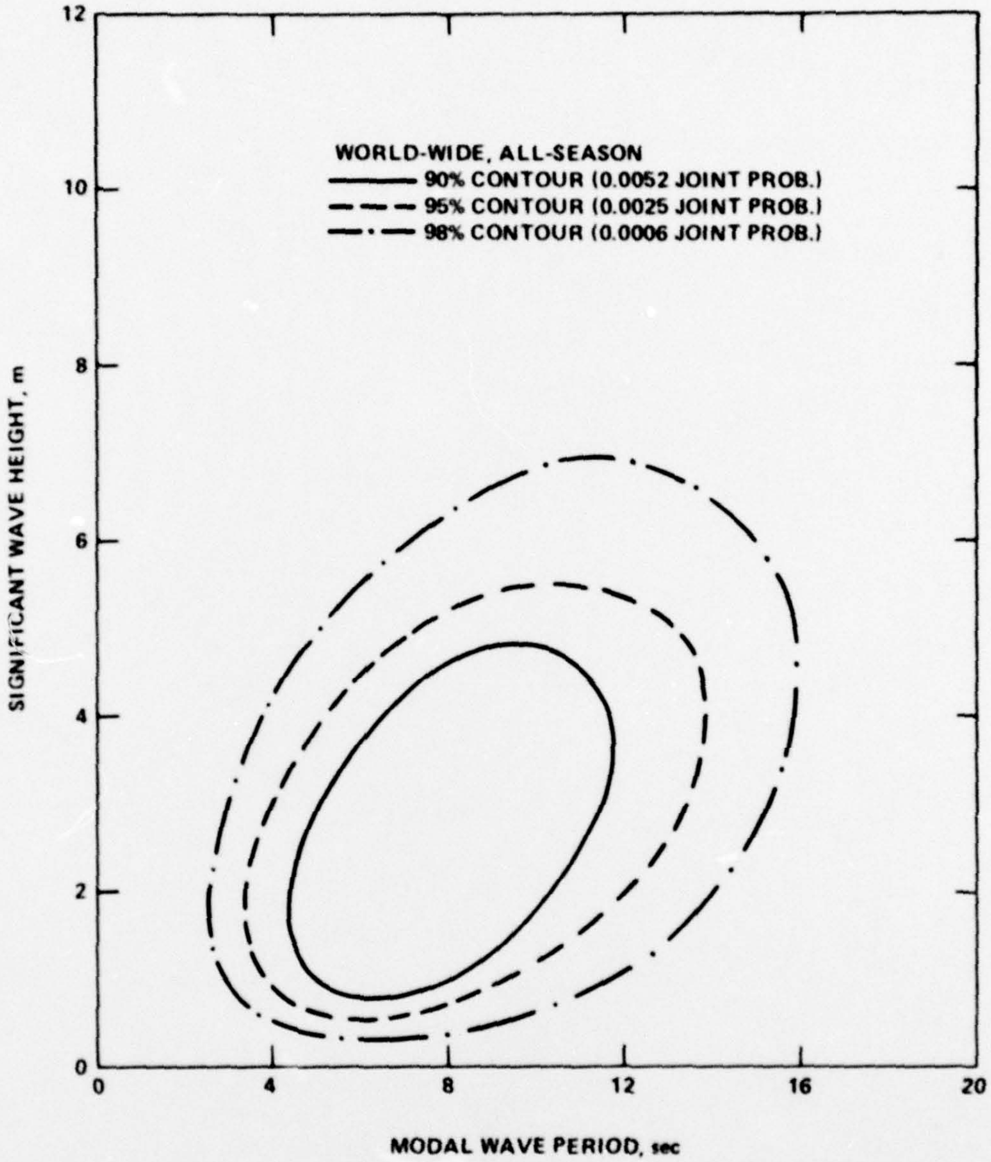

Figure 9 - A Family of Cylinder-Definition Wave Contours for World-Wide, All-Season Operation

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